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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

CIRCULATION CONTROL – A BIBLIOGRAPHY OF DTNSRDC RESEARCH AND SELECTED OUTSIDE REFERENCES

(January 1969 through December 1983)

by

Robert J. Englar
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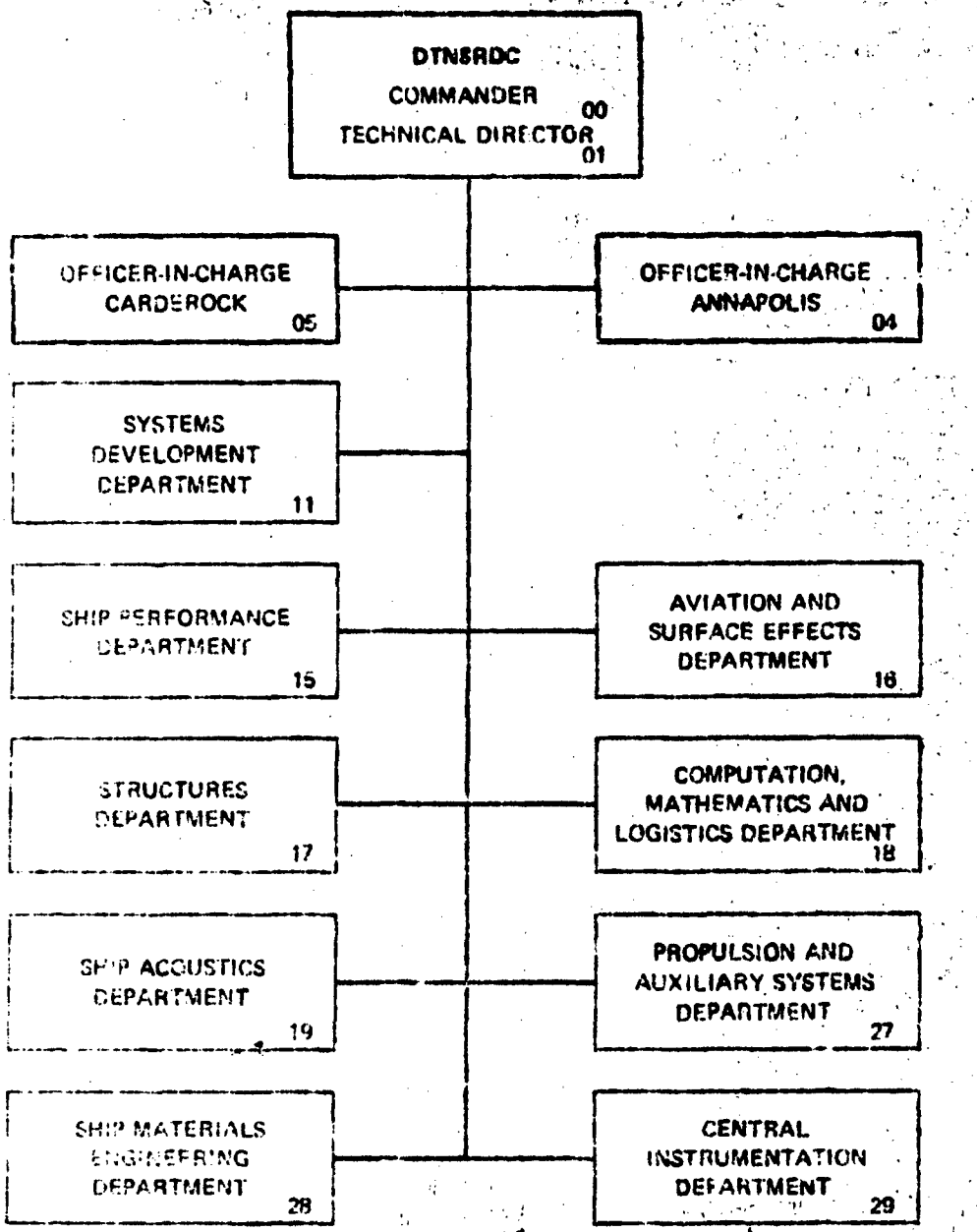

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This report is an update of a previously published bibliography (Report 77-0076) of formal reports, departmental reports, and technical papers by personnel of the Aviation and Surface Effects Department, David W. Taylor Naval Ship Research and Development Center. Included are publications for the period of January 1969 through December 1983. The citations are arranged chronologically and represent the development

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of circulation control technology at the Center over the past several years. Selected outside references pertinent to circulation control are presented in the appendix. Author-supplied Keywords: Circulation control aerodynamics, Boundary layer control, Bluff airfoils, Critical flow number, Elliptic airfoils, Finite wing,

TABLE OF CONTENTS

ABSTRACT

This report is an update of a previously published bibliography (Report 77-0076) of formal reports, departmental reports, and technical papers by personnel of the Aviation and Surface Effects Department, David W. Taylor Naval Ship research and Development Center. Included are publications for the period of January 1969 through December 1983. The citations are arranged chronologically and represent the development of circulation control technology at the Center over the past several years. Selected outside references pertinent to circulation control are presented in the appendix.

ADMINSTRATIVE INFORMATION

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INTRODUCTION

The technology of circulation control (CC) has evolved steadily at DTNSRDC during the past 15 years, and many requests for information have been received from others working on the CC concept. The concept involves the ejection of a thin jet of air (or fluid) over the rounded trailing edge of an otherwise conventional airfoil (hydrofoil). The jet sheet adheres to the trailing edge, moves the stagnation points to the lower surface, and thus controls the circulation and lift on the airfoil. This very powerful method of force generation, essentially independent of the airfoil's inclination to the fluid stream, has many useful applications in the fields of aerodynamics and hydrodynamics. This publication is an update of ongoing work on circulation control.

Citations are arranged chronologically with short abstracts presented for the technical reports and papers published by personnel of the Aviation and Surface Effects Department at DTNSRDC. The brief CC abstracts are included as a guide to researchers in determining whether the complete publication would be of interest.

New citings added to previously published CC bibliographies* begin with item 42. In addition, a selection of references published in the general literature is included in the appendix as an aid to the researcher in the field of circulation control airfoils. These references are by no means intended to be a complete listing, but are representative of those references that have proven useful to DTNSRDC researchers working with the CC concept.

*Englar, R.J., M.B. Stone, and M. Hall, "Circulation Control--An Updated Bibliography of DTNSRDC Research and Selected Outside References," DTNSRDC Report 77-0076, AD A044-762 (Sep 1977).

Stone, M.B. and R.J. Englar, "Circulation Control--A Bibliography of NSRDC Research and Selected Outside References," NSRDC Report 4108, AD A775-284 (Jan 1974).

BIBLIOGRAPHY

1. Williams, R.M., "Some Research on Rotor Circulation Control," Third CAL/AVLABS Symposium on Aerodynamics of Rotary Wing and V/STOL Aircraft, Vol. 2 of Proceedings, Cornell University, Buffalo, New York (18-20 Jun 1969).

Interest in the feasibility of two-bladed stowed-rotor aircraft with relatively high disk loading led to a review of high lift schemes. The primary considerations for the choice of a rotor system were hover efficiency, size, gust insensitivity during the transition, and rigidity.

As a first step, the attempt was made to select the most efficient two-dimensional high lift airfoil section. This was done by defining an equivalent lift-to-drag ratio which included a penalty for the power required for either suction or blowing. The total power penalty can be expressed in terms of a drag coefficient defined by:

Blowing: C_{d_T} = (wake drag + jet momentum flux + ram drag)/qS

Suction: C_{d_T} = (wake drag + suction quantity × pressure drop)/qS

Results show that the method of circulation control by tangential blowing over the rounded trailing edge of an ellipse is superior in efficiency. Also, this section adequately fulfills the other requirements for a stowable rotor with the additional advantage that it may completely eliminate mechanical cyclic control by modulation of the supply air. Inasmuch as considerable research had already been completed at the National Gas Turbine Establishment, this rotor system was ideally suited for further study.

2. Williams, R.M. and H.J. Howe, "Two-Dimensional Subsonic Wind Tunnel Tests on a 20-Percent-Thick, 5-Percent Cambered Circulation Control Airfoil," NSRDC Report ASED-176, AD 877-764 (Aug 1970).

An experimental program has been undertaken to develop circulation control, high lift airfoils for rotary wing vehicle application. The basic method involves ejecting a thin jet sheet of air tangentially over the rounded trailing edge of a thick airfoil, usually of modified elliptic cross section. The jet sheet remains attached to the rounded trailing edge but eventually separates on the underside. The present report presents results for a 20-percent-thick cambered ellipse. The lift, drag, and section equivalent lift-drag ratio data indicate that this model is one of the most efficient high lift airfoils yet tested.

3. Englar, R.J., "Two-Dimensional Transonic Wind Tunnel Tests of Three 15-Percent-Thick Circulation Control Airfoils," NSRDC Report ASED-182, AD A882-075 (Dec 1970).

Two-dimensional transonic wind tunnel tests were conducted on three 15-percent circulation control elliptic airfoils over the range $0.3 \leq M_\infty \leq 0.9$. Model configurations included a pure elliptical shape with both jet flap and tangential upper surface trailing edge blowing and an elliptical shape with a rounded trailing edge and tangential blowing. The rounded trailing edge configuration gave the best performance of the three at low speeds but performance deteriorated rapidly above $M_\infty = 0.55$ due to detachment of the Coanda jet. The elongated trailing edge and associated larger effective radius downstream of the slot enabled the tangentially blown pure ellipse to extend the jet detachment Mach number to 0.7; at this velocity, maximum equivalent lift-to-drag ratios of 22 at C_ℓ of 0.44 and $\alpha = -1.2$ degrees were achieved. The jet flap proved to be inferior to the tangentially blown configuration in all respects except its ability as a thrusting, drag-reducing body.

4. Williams R.M. and C.L. Bernitt, "Theoretical Performance of a Pure Jet Flap Rotor at High Advance Ratios," NSRDC Report ASED-189, AD A726-706 (Dec 1970).

The theoretical performance of a jet flap rotor at advance ratios greater than 1.0 is examined. The rotor is four bladed with purely elliptical airfoils of 15-percent-thickness ratio. Each airfoil has two plenum chambers which supply air to slots located beneath the leading and trailing edges. The rotor operates in cruise at advance ratios greater than unity so that the retreating blade is immersed in reverse flow. The lift and moments are controlled by ejecting a jet sheet out of the trailing edge on the advancing side of the azimuth and both the leading and trailing edge on the retreating side of the azimuth.

Standard blade element theory is used to calculate jet flap rotor performance thrust coefficients representative of actual full-scale rotor operation. It is shown that good performance can be obtained using the jet flap and that substantially better performance can be achieved using a circulation control airfoil.

5. Ottensoser, J., "Description and Calibration of a Wall Balance System for a 15- by 20-Inch Subsonic Wind Tunnel," NSRDC Report ASED-196 (Feb 1971).

A wall balance for a 15- by 20-inch subsonic wind tunnel was built and calibrated. This system uses a set of three concentric rings on each of the two walls of the tunnel test section to measure lift, drag, and pitching moment. Maximum loads are $\pm$300 pounds in lift and $\pm$50 pounds drag. Calibration results indicate that the balance is reliable to within 1 percent in lift and drag. Moment results are only fair--at best their accuracy is only t thin 5 percent.

6. Englar, R.J. and R.M. Williams, "Design of a Circulation Control Stern Plane for Submarine Application," NSRDC Report ASED-200, AD A901-198 (Mar 1971).

A nondeflecting circulation control (CC) submarine stern plane was designed in order to provide maneuverability control and eliminate the possibility of catastrophic crash dives due to stern plane jamming. Symmetric elliptic sections with tangential blowing out of upper and lower slots over a rounded trailing edge were selected because of their high lift and equivalent aerodynamic (hydrodynamic) efficiencies. The CC model stern plane so designed was restricted by the requirement to maintain the same planform as a conventional stern plane, by the existence of a large boundary layer on the main body, and by the additional requirement of zero deflection. With moderate blowing, it was able to meet or exceed the prescribed lifting (maneuvering) requirments for the conventional deflecting control surface. In the event of a blowing failure, the fixed nature of the plane provides inherent stability.

The technical note includes a detailed design procedure, supporting experimental data, and the final geometry of the blown model stern plane. Also included is a similar study on an alternate blown configuration with end plates which demonstrated improved performance over the first design.

7. Englar, R.J., "Two-Dimensional Subsonic Wind Tunnel Tests of Two 15-Percent-Thick Circulation Control Airfoils," NSRDC Report ASED-211, AD A900-210 (Aug 1971).

Two relatively thin circulation control (CC) elliptic airfoils were tested subsonically to determine their characteristics as proposed helicopter rotor tip sections. These airfoils employ tangential trailing edge (Coanda) blowing and previous tests had demonstrated very promising transonic characteristics. It was the purpose of the subsonic retests to determine whether these thin sections could generate equally impressive characteristics at low speeds. Because of its more forward slot location, the 15-percent-thick pure elliptic section displayed effective subsonic operation at positive angle of attack, reducing drag while producing lift coefficients up to 3.5. The rounded trailing edge configuration, with further aft slot and better Coanda deflection of the jet, generated lift coefficients up to 4.25 (with a preference for negative incidence) but experienced higher drag levels. Leading edge separation limited the performance of both sections because of their small nose radii and low test Reynolds number. At a fixed momentum cofficient, performance improved as slot height was reduced. This was due primarily to higher energy levels in the jet sheet, but the lower bound on slot height was limited by boundary layer buildup in very small nozzles. Circulation control gave both CC sections far greater lift capabilities than the more conventional NACA 0012 blade section, but their equivalent efficiency was less at positive incidence due to blowing power requirements.

8. Williams, R.M. and R.A. Hemmerly, "Determination of the (Ideal Practical) Hover Efficiency of Circulation Control Rotors," NSRDC Report ASED-212, AD A902-068 (Aug 1971).

An approximate analysis of the maximum hover performance of a Circulation Control Rotor is presented. Closed form equations are developed which conveniently show the contribution of the induced, profile, compressor and coriolis powers in terms of the basic airfoil equivalent lift to drag ratios. A range of rotor taper ratios and solidities are examined under the constraint of ideal twist distribution. A comparison is made with a conventional rotor using a NACA 0012 reference airfoil. It is demonstrated that the circulation control rotor can achieve comparable overall hover efficiencies (Figure of Merit) at significantly higher values of rotor thrust coefficient to solidity ratio than conventional rotors. The implications of these characteristics for helicopter design is then discussed briefly.

9. Williams, R.M., "Analysis of the Hover Performance of a High Speed Circulation Control Rotor," NSRDC Report ASED-221, AD 904-474 (Aug 1971).

A method for calculating the detailed hover performance of any arbitrary circulation control rotor is presented. The method includes such higher order effects as non-uniform inflow, internal ducting losses and experimental airfoil data. Calculations were performed on an untwisted constant chord blade with varying section thickness and camber. Hover Figures of Merit exceeding 0.80 are calculated for this rotor at thrust coefficient to solidity ratios of 0.20. The optimum pitch angle is determined for each thrust coefficient. The effects of slot height and tip Mach number are also analyzed. A comparison is made with a coventional rotor system of the same solidity.

10. Englar, R.J., "Two-Dimensional Subsonic Wind Tunnel Tests of a Cambered 30-Percent-Thick Circulation Control Airfoil," NSRDC Report ASED-201, AD A913-411 (May 1972).

A relatively thick Circulation Control (CC) elliptic airfoil section with a thickness-to-chord ratio of 0.30 and a circular arc camber of 1.5 percent at the midchord was tested subsonically to determine its aerodynamic properties as a mid-span blade section on a blown helicopter rotor. The two-dimensional tests established the ability of the section to generate the required lift at low and negative incidence. Lift coefficients up to 6.5 were produced at moderate momentum coefficient ($C_\mu \leq 0.24$). High drag of the unblown bluff ellipse was greater reduced by the application of very moderate blowing, and equivalent efficiencies of 47 (including power required for blowing) were generated at $C_\ell = 1.9$. Section performance was found to be heavily influenced by upper and lower aft surface flow separations, especially at the larger positive and negative angles of attack. In addition, both low Reynolds number and an increase in slot height were detrimental to section lift capability. Nevertheless, the ability to operate at high lift coefficients

essentially independent of angle of attack, and with large lift augmentation from relatively low blowing, promises to provide an effective blade section for heavy lift application.

11. Williams, R.M. and E.O. Rogers, "Design Considerations of Circulation Control Rotors," Paper 603 presented at 28th National Forum of the American Helicopter Society, Washington, D.C. (18-19 May 1972).

The concept of circulation control by means of tangential blowing about bluff trailing edge airfoils is introduced. The major aerodynamic characteristics which are applicable to rotor design are described. These include such revolutionary features as the generation of lift independent of velocity (in the region of boundary layer control) and the development of efficiencies comparable to present airfoils but at much higher lift coefficients. The application of these new airfoils to a rotor with no mechanical cyclic control is next discussed, and it is shown that a broad range of applications is possible. Significant improvements in rotor thrust capability, hover efficiency, cruise efficiency, and weight efficiency are predicted. Some experimental results are shown. A very high-speed helicopter design and a heavy lift helicopter design are used to illustrate the operational improvements which may be expected with the circulation control concept. It is demonstrated that this rotor may offer a breakthrough in helicopter design and performance resulting in a virtual doubling of productivity.

12. Rogers, E.O., "Critical Mach Numbers of Circulation Control Airfoils as Determined by Finite-Difference Methods," NSRDC Report ASED-273, AD A909-874 (Aug 1972).

The critical Mach number of several circulation control elliptic airfoils was calculated for various circulation and angle-of-attack conditions. The full inviscid compressible flow equations were solved by finite-difference relaxation methods. The sections examined are candidates for use on helicopter rotor blades. Comparisons with conventional sections indicated that the elliptic circulation control airfoils had a significantly higher critical Mach number.

13. Williams, R.M., "Recent Developments in Circulation Control Rotor Technology," Meeting of Advisory Group for Aerodynmaics R&D (Aerodynamics of Rotary Wings), AGARD-CPP-111, Marseilles, France (13-15 Sep 1972).

The results of recent research on the historical concept of applying circulation control to rotor blades are presented. A high-speed helicopter application was used to illustrate the potential of this rotor for a major breakthrough in the areas of rotor efficiency, parasite drag, and weights, leading to a large improvement in aircraft productivity. Details of the hover, transition, and high-speed cruise performance are presented. Some problems of autorotation, vibrations, and blade dynamics are also discussed.

14. Englar, R.J. and J. Ottensoser, "Calibration of Some Subsonic Wind Tunnel Inserts for Two-Dimensional Airfoil Experiments," NSRDC Report ASED-275, AD 913-412 (Sep 1972).

Parallel wall inserts were installed in the Naval Ship Research and Development Center 8- × 10-foot subsonic tunnel to create a 3- × 8-foot channel to serve as a high flow quality two-dimensional test section for high lift testing. A detailed flow survey indicated good flow uniformity, negligible angularity, a thin wall boundary layer at the model station, and a pronounced effect of trailing edge wall flaps on controlling test section dynamic pressure. A pair of two-dimensional airfoil sections tested in the facility displayed good agreement with reference data in lift and pressure distribution, but some disagreement in wake rake drag data. The strong influence of model lift on test section dynamic pressure measurement was noted, and a measurement technique was developed which was independent of the static pressure field propagating from the airfoil.

15. Englar, R.J. and R.M. Williams, "Test Techniques for High Lift Two-Dimensional Airfoils with Boundary Layer and Circulation Control for Application to Rotary Wing Aircraft," Canadian Aeronautics and Space Journal, Vol. 19, No.3, pp. 93-108 (Mar 1973); also published as NSRDC Report 4645, AD A01[illegible]-623 (Jul 1975).

Extensive testing experience with very high lift monoelement blown airfoils to be employed by rotary wing aircraft has necessitated the development of unconventional two-dimensional test techniques. The experimental and analytical results presented here should assist future investigators to conduct similar tests accurately.

The primary problem of high lift two-dimensional testing, wall boundary layer separation due to severe adverse pressure gradients on the model, is discussed as are the serious errors introduced by this phenomenon. Closely related is the preference for pressure instrumenation (both lift and drag) over the simpler but considerably less accurate force balance. The detailed discussion concerns the additional considerations which must be given to blown airfoil testing, e.g., blowing coefficients, necessary modification to pitot-traverse drag calculations, and definition of an equivalent lift-drag ratio which takes into account the penalty for blowing. Such additional test problems as wall and blockage corrections, Reynolds number effects, leading edge separation, and flow visualization are also addressed.

16. Wilkerson, J.B., "Design and Performance Analysis of a Prototype Circulation Control Helicopter Rotor," NSRDC Report ASED-290, AD A912-213 (Mar 1972).

A Circulation Control Rotor (CCR) has been designed for application to existing, conventional-speed helicopters of the 5000 to 10000 pound weight class. A design methodology is shown which tends to minimize rotor induced power in hover while operating at near maximum airfoil section efficiency. The particular design was constrained by conventional disc loadings and blade tip speeds to be consistent with

available helicopter engine/transmission combinations. The design is near optimum within these constraints and current available data. Circulation control airfoil and slot geometry design considerations are shown. Tip speed, solidity and disc loading were varied to show performance sensitivity to those parameters and to define the conditions of best overall rotor aerodynamic efficiency. The constrained CCR design was found to operate best at a thrust coefficient/solidity ratio around 0.12. At this condition hover Figure of Merit improved with increased disc loading, while cruise aerodynamic efficiency was relatively insensitive to disc loading changes. Overall performance exceeded or was equal to that of conventional rotor systems for the same weight class vehicle.

17. Stone, M.B., "Higher Harmonic Circulation Control Rotor Model, Model Instrumentation, and Data Acquisition," NSRDC Report ASED-288, AD A765-320 (Apr 1973).

A higher harmonic Circulation Control Rotor (CCR) was tested in the 8- × 10-foot subsonic wind tunnel at various advance ratios, blade tip Mach numbers, blowing air pressures, shaft angles, and collective angles. The model was instrumented with strain gages, pressure transducers, thermocouples, magnetic pickups, and a pitch-roll trim resolver. This information was recorded on an anlog to digital data acquisition system and on FM tape recorders for later digitization.

The purpose of this volume is to provide descriptive documentation of the model instrumentation and data acquisition portion of the test, and no attempt has been made to elaborate on helicopter or higher harmonic theory.

18. Reader, K.R., "Evaluation of a Pneumatic Valving System for Application to a Circulation Control Rotor," NSRDC Report 4070, AD A910-982 (May 1973).

A cam-type pneumatic valving system has been developed to provide helicopter rotor control/trim forces. This valving system provides both first and second harmonic rotor control by means of modulating both blade pressures and mass flow rates. Data are presented for (1) constant one-per-rev and two-per-rev air modulation, (2) constant and tapered slot distributions, (3) two pipe volumes, and (4) three cam-nozzle gap distances.

The present study demonstrated that air pressure and mass flow rate can be modulated by means of a simple cam valve system. As the gap between the periphery of the cams and the nozzle was increased for a given cam geometry, the mean pressure and mass flow rate increased and the peak-to-peak pressure and mass flow rate decreased. It was also demonstrated that a smooth transfer of the total pressure and mass flow rate occurred in going from a one- to a two-per-rev component (or vice versa).

19. Wilkerson, J.B. et al., "The Application of Circulation Control Aerodynamics to a Helicopter Rotor Model," Paper 28 presented at 29th Annual Forum of American Helicopter Society, Washington, D.C. (10-11 May 1973).

On the basis of several years of two-dimensional research in the field of circulation control airfoils, a higher harmonic CCR model was designed, built, and tested at NSRDC. Unique features of the model included blades with elliptical-shaped circulation control airfoils and a simple cyclic control mechanism based on the variation of blade pressure rather than blade pitch. The model demonstrated that trimmed flight could be achieved without moving parts other than the rotating blades and, further, that the high lift capability and efficiency of circulation control airfoils could be extended into the three-dimensional regime.

Aerodynamic trends displayed by the model were coupled with two-dimensional results to improve the theoretical programs used to predict model performance. Variables such as slot height-to-chord ratios, slot height-to-trailing edge radius ratio, Reynolds number, and Mach number have been identified as factors which significantly affect the performance of circulation control airfoils These effects have therefore been incorporated into the programs. Good agreement between theory and model results have led to a second generation rotor design.

20. Rogers, E.O., "Numerical Solution of Subcritical Flow Past Airfoils," NSRDC Report 4112, AD A046-619 (May 1973); also published as University of Maryland M.S. Thesis, Department of Aerospace Engineering (1973).

A finite-difference solution technique has been developed for subsonic two-dimensional inviscid flow past lifting airfoils. This work is an adaptation of the method used by Sells (1967). The full governing equations of compressible flow are written in terms of a translated velocity potential which is continuous throughout the flow field. This simplifies solutions for bluff airfoils (no Kutta condition) where both angle of attack and lift coefficient are specified. The computational plane is the interior of a unit circle obtained by mapping the flow field into the interior of the circle. A line over-relaxation matrix method is used for solution of the partial differential equation which in the iteration scheme is coupled with an algebraic equation. The numerical procedure is accurate and well behaved for all subsonic flow conditions.

21. Englar, R.J., "Subsonic Wind Tunnel Investigation of the High Lift Capability of a Circulation Control Wing on a 1/5-Scale T-2C Aircraft Model," NSRDC Report ASED-299, AD A781-856 (May 1973).

A Circulation Control Wing, formed by the deflection of a 15-percent chord flap through 180 degrees to produce a circular cylinder trailing edge with tangential upper surface blowing, was applied to a 1/5-scale T-2C aircraft model. The flap span/wing span ratio was 0.495, consistent with the conventional aircraft. Subsonic investigations were conducted in the Naval Ship Research and Development

Center (NSRDC) 8- by 10-Foot North Wind Tunnel over a dynamic pressure range of 5 to 41 psf (Reynolds number based on mean aerodynamic chord of 0.60 to 1.68 million). Flap deflection was varied from 0 to 180 degrees, thus comparing the configurations of blown flap (moderate-to-high lift and lower drag for take-off) and the circular Coanda trailing edge (high lift and high drag for landing). At a Reynolds number of 1.43 million, a maximum lift coefficient of 3.33 was generated by the Circulation Control Wing at a momentum coefficient of 0.156, compared to $C_{L_{max}} = 1.70$ for the conventional aircraft with a 37-percent chord single slotted flap deflected 33 degrees. Performance was limited by part-span (as opposed to full-span) blowing and large vorticity generated at the blown-unblown junction of the wing.

22. Englar, R.J., "Experimental Investigation of the High Velocity Coanda Wall Jet Applied to Bluff Trailing Edge Circulation Control Airfoils," NSRDC Report ASED-308, AD A771-690 (Jun 1973); also published as M.S. Thesis, University of Maryland, Department of Aerospace Engineering (Jun 1973) and as NSRDC Report 4708, AD A019-417 (Sep 1975).

A two-dimensional experimental investigation, intended to probe the mechanism for loss of performance of circulation control elliptic airfoils in compressible flow, was conducted subsonically on a 20-percent thick modified elliptic profile employing high Coanda wall jet velocities. The results include detailed pressure distributions (both normal and chordwise) and trailing edge shear stress measurements made with a hot film anemometer for a range of jet slot heights and jet total pressures corresponding to high subsonic, sonic, and supersonic jet velocities. Jet Mach numbers of almost 1.3 were found to have no adverse effects on the airfoil performance, and the degrading jet detachment phenomenon was never encountered. Significant differences in the jet flow field with and without an external free-stream were noted, as was the deviation of the static pressure across the jet from a constant value as assumed in conventional boundary layer analysis. Airfoil lift performance was found to vary with slot height, while location of the jet separation point was provided by the detailed shear stress measurement. Also discussed is the calibration and use of the hot film shear stress probe.

23. Englar, R.J., "Investigation into and Application of the High Velocity Circulation Control Wall Jet for High Lift and Drag Generation on STOL Aircraft," AIAA Paper No. 74-502 presented at the AIAA 7th Fluid and Plasma Dynamics Conference, Palo Alto, California (17-19 Jun 1974); also published as DTNSRDC Report 76-0142, AD A034-619 (Nov 1976).

The concept of circulation control by tangential upper surface blowing over a circular trailing edge has been investigated for application to fixed wing STOL aircraft. Experimental investigations on both two- and three-dimensional airfoils employing nominal blowing have demonstrated lift gains almost triple that of the conventional flapped airfoil and associated large increases in drag (which, in

addition to the high lift, further reduces landing velocities and distances). An additional two-dimensional investigation into the basic fluid mechanics of the concept has shown that jet Mach numbers considerably above choke produced no adverse effects on the mechanism of the trailing edge Coanda flow, but instead yielded additional lift gains. These results appear quite promising where high lift generation is desired for a STOL aircraft having a nominal amount of auxiliary bleed air available, but where substitution of increased pressure ratios can produce added jet velocity to obtain the required momentum (blowing) coefficient.

24. Ottensoser, J., "Two-Dimensional Subsonic Evaluation of a 15-Percent Thick Circulation Control Airfoil with Slots at Leading and Trailing Edges," NSRDC Report 4456, AD A785-230 (Jul 1974).

A 15-percent-thick circulation control elliptical airfoil section with slots at both leading and trailing edges for tangential blowing was evaluated in a subsonic wind tunnel to determine its potential for high-speed (300-400 knot) helicopter rotor systems. Fore-and-aft slot utilization was determined by local flow direction over the blade as it revolved around the azimuth. Aerodynamic performance was not affected by the addition of an unblown leading edge slot except beyond the usable positive angle of attack range where some loss in lift and increase in drag were noted. At equal plenum pressures, simultaneous blowing from the leading and trailing edges resulted in a decrease in lift, and increase in drag, and a more positive pitching moment than trailing edge blowing alone. However, for its intended application to the retreating blade area of the rotor disk, the dual slotted airfoil can provide positive lift for both fore and aft flow directions—a condition which is not readily achievable with the coventional rotor airfoil.

25. Englar, R.J., "Subsonic Two-Dimensional Wind Tunnel Investigations of the High Lift Capability of Circulation Control Wing Sections," NSRDC Report ASED-274, AD A024-346 (Apr 1975).

Two series of Circulation Control Wing airfoil sections, formed by the conversion of the sharp trailing edge into a circular bluff surface with tangential upper surface blowing, were evaluated subsonically to determine their high lift characteristics as potential STOL wing sections. Parameters investigated which had noticeable effect on the blown airfoil performance include leading edge devices (type of device and degree of deflection), trailing edge configuration (radius, slot location, deflection, etc.), Reynolds number, airfoil incidence, momentum coefficient, slot height, and nozzle pressure ratio. Maximum lift coefficients roughly triple those of flapped conventional sections were generated at incidence slightly less than the conventional stall angles and at blowing rates obtainable from bleed of state-of-the-art turbojet engines. An experimental investigation into the lift augmenting effects of pulsed unsteady blowing was conducted on a smaller radius trailing edge configuration. An additional investigation was conducted to determine the effects of spoilers or similar disturbances ahead of the jet exit. The results of the above investigations provide a data base for the prediction of the aerodynamic characteristics of aircraft employing Circulation Control trailing edges to increase their STOL capability.

26. Montana, P.S., "Experimental Investigation of Three Rotor Hub Fairing Shapes," NSRDC Report ASED-333, AD A012-537 (May 1975).

A series of subsonic wind-tunnel evaluations was undertaken to establish minimum drag fairings for helicopter hubs as part of the Helicopter Drag Technology Program. The data reported herein were taken to investigate the flow phenomena affecting helicopter rotor hubs. Three large, 25-percent thick, analytically faired hubs were evaluated (both with and without simulated rotor blade shanks) over a wide range of angles of attack at full scale Reynolds numbers. Forces, moments, and pressures were measured on the hubs. Of the three fairing shapes evaluated, the reflex curvature fairing was shown to have significantly lower drag at small angles of attack than the other shapes.

27. Englar, R.J., "Circulation Control for High Lift and Drag Generation on STOL Aircraft," AIAA Journal of Aircraft, Vol. 12, No. 5, pp. 457-463 (May 1975).

The concept of circulation control by tangential upper surface blowing over a circular trailing edge has been investigated for application to fixed wing STOL aircraft. Experimental investigations on both two- and three-dimensional airfoils employing nominal blowing have demonstrated lift gains double to triple that of the conventional flapped airfoil, and associated large increases in drag (further reducing landing velocities and distances). An additional two-dimensional investigation into the basic fluid mechanics of the concept has shown that jet Mach numbers considerably above choked produced no adverse effects on the mechanism of the trailing edge Coanda flow, but instead yielded additional lift gains. These results appear quite promising where high lift generation is desired for a STOL aircraft having a nominal amount of auxiliary bleed air available, but where substitution of increased pressure ratios can produce added jet velocity to obtain the required momentum (blowing) coefficient.

28. Wilkerson, J.B. and D.W. Linck, "A Model Rotor Performance Validation for the CCR Technology Demonstrator," Preprint 902 presented at 31st Annual National Forum of the American Helicopter Society, Washington, D.C. (May 1975); also published in Journal of the American Helicopter Society, Vol 21, No. 4 (Oct 1976).

Circulation control technology has been further developed at the Naval Ship Research and Development Center by wind tunnel and hover stand evaluations of a second rotor model—the Circulation Control Rotor (CCR). This two-bladed model was preceded by the four-bladed Higher Harmonic Circulation Control (HHCC) rotor. The first model proved that circulation control could be used for cyclic lift control at forward speeds without the use of cyclic pitch. An improved CCR design was accomplished with a theoretical prediction program which was revised by using the results obtained for HHCC rotor. The performance of both rotor models is compared and an explanation given of how the trends of the CCR data were used to refine the prediction programs. The results of the extensive correlation effort are shown for forward flight and hover. Knowledge gained from the two CC rotors has been applied to the aerodynamic design of the full-scale technology demonstrator, the Kaman XH2/CCR.

29. Abramson, J., "Two-Dimensional Subsonic Wind Tunnel Evaluation of a 20-Percent-Thick Circulation Control Airfoil," NSRDC Report ASED-331, AD A027-164 (Jun 1975).

A circulation control uncambered elliptic airfoil section with a thickness-to-chord ratio of 0.20 was tested subsonically to determine its aerodynamic characteristics. Lift coefficients up to 5 were produced at momentum coefficients of 0.24. The initially high unblown drag coefficients, characteristic of bluff trailing edge airfoils, were greatly reduced at low values of momentum coefficient. It was therefore possible to produce equivalent lift-to-drag ratios in excess of 30 when $C_\ell = 1.0$. The ability to produce high lift coefficients essentially independent of angle of attack is indicated by the results of this investigation.

30. Hemmerly, R.A., "Subsonic Wind Tunnel Investigation of a Semi-Span Jet Flapped Wing Designed Primarily for High Speed Flight," NSRDC Report ASED-351, AD A024-798 (Jun 1975).

The low speed aerodynamic characteristics of an 18-percent scale, semi-span jet flapped wing designed primarily for transonic maneuverability were investigated in the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) 8- × 10-Foot Subsonic Wind Tunnel. These low speed characteristics were obtained to aid in determining if adequate STOL performance could be obtained by a high speed jet flapped wing, thus eliminating the need for additional high lift devices required solely for the landing and takeoff modes of operation. The structure of this investigation provided a data basis for a jet flapped wing with and without a glove. During the investigation the maximum lift coefficient obtained was 1.96 corresponding to a blowing coefficient and angle of attack of 0.326 and 13.6 degrees, respectively. This is approximately a 280-percent improvement in lift over the wing at the same incidence with no blowing. Evaluation of the roll power at the low speed condition indicates that adequate power is available to control an aircraft equipped with a gloved jet flapped wing in the takeoff and landing modes. In general, subsonic performance of the gloved wing was limited in this investigation by large vorticity generation and detached flow.

31. Williams, R.M., "Application of Circulation Control Rotor Technology to a Stopped Rotor Aircraft Design," presented at the First European Rotorcraft and Powered Lift Aircraft Forum, Southampton, England (22-24 Sep 1975); also published as DTNSRDC Report 4574, AD A209-168 (Dec 1975).

This paper presents the application of circulation control rotor (CCR) technology to a revolutionary new aircraft concept--the X-Wing stopped rotor V/STOL. This design affords the potential for major advances in rotary wing aircraft speed, range-payload, productivity, and cost through the application of highly innovative aerodynamic and structural design. The technology base for the concept has been derived from almost 6 years of related CCR aerodynamic and structural design studies

at the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) and from earlier research in the United Kingdom. Additional design insight has been gained from the experience of various stopped and stowed rotor concepts of the 1960's and also from more recent studies of th NASA "oblique wing" transonic transport concept.

32. Reader, K.R. and J.B. Wilkerson, "Circulation Control Applied to a High Speed Helicopter Rotor," Preprint No. 1003 presented at 32nd Annual National V/STOL Forum of the American Helicopter Society, Washington, D.C. (May 1976).

An advanced circulation control rotor concept identified as the Reverse Blowing-Circulation Control Rotor (RE-CCR) is discussed from the standpoint of general requirements for high speed flight. This discussion centers on a rotor solidity ratio compromise between hover, transition and cruise requirements. It is shown that the critical solidity requirement occurs in transition where high lift capability is needed while maintaining rotor moment trim. An analytical and experimental investigation of the aerodynamic environment in the transition flight regime (advance ratios of 0.5 to 1.4) indicates that large local yawed flow angles do not severely affect the lift augmentation and maximum lift coefficient of circulation control airfoils.

An RB-CCR model was designed and tested at the David W. Taylor Naval Ship Research and Development Center (DTNSRDC). This rotor is unique in its employment of a special circulation control airfoil which has a slot in the leading and trailing edge. The results of several test programs verified the capability of the rotor to perform efficiently in hover and at advance ratios up to 4.0. The model data also demonstrated that the rotor is capable of developing sufficient lift to fly through the critical advance ratio of 0.7.

33. Reader, K.R., "A Control System for the Wind Tunnel Model of a Reverse-Blowing Circulation Control Rotor (RB-CCR)," DTNSRDC Report 76-0062, AD A026-548 (May 1976).

A pneumatic valving system has been developed to provide cyclic and collective control inputs for a circulation control type rotor over an advance ratio range of 0 to 2.0. The design method and experimental techniques utilized in developing the control system for a wind tunnel model of the reverse-blowing circulation control rotor (RB-CCR) are discussed and a tradeoff is presented between two control systems which have potential for the necessary requirements. A cam-collector nozzle system is considered a better choice for the model rotor configuration than a cam-collector ring control system. It was concluded that a system to control the RB-CCR wind tunnel model can be designed by employing the proper area relationships and adhering to a simple design procedure.

34. Williams, R.M., R.T. Leitner, and E.O. Rogers, "X-Wing: A New Concept in Rotary Wing VTOL," presented at the American Helicopter Society Symposium on Rotor Technology, Philadelphia (Aug 1976).

The current status of the theoretical and experimental analysis of an advanced Circulation Control (CC), stopped rotor concept called X-Wing is presented. Modifications to classical fixed wing theory to properly represent circulation control aerodynamics and the interference effects of fore and aft swept wings for the stopped rotor mode are discussed. The results generated from this modified theory are compared with experimental results obtained on a model rotor. Theoretical drag estimation of a full-scale vehicle indicates that the total vehicle parasite drag compares favorably with current fixed wing aircraft. Design tradeoffs for the full-scale aircraft show that for missions requiring less than 30 minutes of hover, a vehicle designed without collective pitch is possible. An elastic slot design is also considered and is shown to enhance both transition and fixed wing performance. The analysis of transition performance is discussed with recommendations of areas needing further study. The results of both the theoretical and experimental analysis of all flight modes show that no fundamentally limiting problems exist at this stage of development.

35. Wilkerson, J.B., "Aeroelastic Characteristics of a Circulation Control Wing," DTNSRDC Report 76-0115, AD A033-328 (Sep 1976).

Static aeroelasticity is examined for a wing with circulation control (CC) airfoils. The airfoils use tangential blowing over a rounded trailing edge to provide a lift augmentation proportional to the jet momentum of the blown air. Airfoil lift and pitching moment magnitudes are dependent on both angle of attack and jet momentum. In combination with an elastic structure, this double dependence of lift and moment can lead to a CC reversal condition, which is analogous to aileron reversal. Increases in jet momentum beyond the reversal point result in lift decreases. Boundaries for torsional divergence and CC reversal are theoretically examined for the simple two-dimensional case and then for a three-dimensional wing. The wing analysis uses a modified lifting line theory and two-dimensional CC airfoil data to evaluate the behavior of a circulation control wing (CCW). Two parameters, lift effectiveness and control effectiveness, define the behavior of an elastic CCW relative to that of a rigid CCW. A modified version of the wing analysis is used for comparison to wind tunnel data from a CCW model. The model had a root attachment device which allowed rigid body wing torsional deflections in response to the aerodynamic pitching moments.

Stall flutter conditions were encountered which involved only the wing bending mode oscillating at the first cantilevered natural frequency. A first-order explanation of the flutter is provided by two-dimensional considerations. It is shown that the wing stall flutter boundaries may be established from the two-dimensional analysis by proper scaling and by establishing an aerodynamic equivalence.

The theory was in good agreement with wind tunnel evaluations on a model CC wing. Because of the large geometric twist in the available model, portions of the wing were at or near angle-of-attack stall conditions even though blowing maintained significant levels of lift coefficient. Such conditions are unique to CC airfoils. This caused some difficulty in obtaining a solution with the lifting line theory which would provide a numerically stable and convergent iteration. The approach used in conjunction with the modified lifting line theory and two-dimensional airfoil data is believed to be the first such analysis, notwithstanding the establishment of divergence and reversal boundaries.

36. Reader, K.R. and J.B. Wilkerson, "Circulation Control Applied to a High Speed Helicopter Rotor," DTNSRDC Report 77-0024 (Feb 1977).

An advanced circulation control rotor concept identified as the Reverse Blowing-Circulation Control Rotor (RB-CCR) is discussed from the standpoint of general requirments for high speed flight. This discussion centers on a rotor solidity ratio compromise between hover, transition and cruise requirements. It is shown that the critical solidity requirement occurs in transition where high lift capability is needed while maintaining rotor moment trim. An analytical and experimental investigation of the aerodynamic environment in the transition flight regime (advance ratios of 0.5 to 1.4) indicates that large local yawed flow angles do not severely affect the lift augmentation and maximum lift coefficient of circulation control airfoils.

An RB-CCR model was designed and tested at the David W. Taylor Naval Ship Research and Development Center (DTNSRDC). This rotor is unique in its employment of a special circulation control airfoil which has a slot in the leading and trailing edge. The results of several test programs verified the capability of the rotor to perform efficiently in hover and at advance ratios up to 4.0. The model data also demonstrated that the rotor is capable of developing sufficient lift to fly through the critical advance ratio of 0.7.

37. Englar, R.J., L.A. Trobaugh, and R.A. Hemmerly, "Development of the Circulation Control Wing to Provide STOL Potential for High Performance Aircraft," AIAA Paper No. 77-578 presented at AIAA/NASA Ames V/STOL Conference, Palo Alto, California (6-8 Jun 1977).

Research and development are being conducted at the David W. Taylor Naval Ship Research and Development Center to investigate the STOL capability of the Circulation Control Wing (CCW) concept on high performance aircraft. This high lift system, which employs tangential blowing over a rounded trailing edge and requires mass flows characteristic of state-of-the-art turbine engine bleed, has demonstrated the ability to more than double the lift capability of conventional Navy and Marine aircraft. The resulting reduced takeoff and landing speeds and distances plus increased overload capability are achieved without severe compromise of wing structure, weight, or engine arrangement, and without large quantities of ducted hot gas.

Based on these anticipated benefits and the results of existing experimental investigations, a program has been initiated to demonstrate the STOL capability of the CCW concept applied to a full scale A-6 flight demonstator aircraft. The present paper will address the experimental development and optimization of the CCW system on an A-6 model and will present predicted full scale STOL performance gains for the flight demonstrator.

38. Reader, K.R., "Hover Evaluation of the Circulation Control High Speed Rotor," DTNSRDC Report 77-0034, AD A040-921 (Jun 1977).

As part of the on-going Circulation Control Rotor Technology Program at the David W. Taylor Naval Ship Research and Development Center (DTNSRDC), a high-speed rotor model designated the RB-CCR (reverse blowing circulation control rotor) was evaluated in the hover mode. The experiment utilized an existing DTNSRDC model hover stand and the model was tested as two- and four-bladed rotor with several rotor configurations.

Major findings are summarized as follows:

1. The best rotor performance in hover at a particular C_T/σ is established from tradeoffs between tip Mach number and blade collective pitch angle.
2. With the leading edge slot covered, augmentation of rotor thrust was independent of tip Mach number. Thrust augmentation was reduced by approximately 18 percent when the leading edge slot was exposed.
3. The increased power required in hover due to the exposed leading edge slot indicates that some means of closing off the leading edge slot (when not in use) should be incorporated into a full-scale rotor. (One suggested means might be a flexible slot lip with slot opening a function of blade duct pressure.)
4. There was a small reduction in figure of merit for the trailing edge slot closed off (slot cutout) for 30-percent radius and as much as a 6-percent reduction in performance for a 50-percent slot cutout.

In general the hover tests demonstrated that a good figure of merit can be obtained over a large range of collective pitch angles. A comparison of configurations at various collective angles showed a steady improvement in performance with increasing collective pitch angle (up to $\Theta_c = 6$ deg). Indeed, the RB-CCR model demonstrated that the high-speed rotor can hover with a zero mechanical collective pitch angle at a figure of merit of about 0.50.

39. Furey, R.J. and R.E. Whitehead, "Static Evaluation of a Circulation Control Centrifugal Fan," DTNSRDC Report 77-0051, AD A041-463 (Jun 1977).

The static characteristics of a circulation control (CC) fan were determined to demonstrate the feasibility of the CC concept as a means of meeting the lift system requirements of a large, open ocean capable, surface effect ship (SES)—these requirements being variable performance, at constant RPM, of sufficient range

to provide for heave alleviation when operating at high speeds in advanced sea-states. The scope of the program included two solidity ratios within the model centrifugal impeller and, in effect, two volutes. The better performing combination of these variations was the low solidity (σ = 0.65) impeller mated with a reduced internal volume volute. This fan demonstrated a flow rate increase of 100 percent over that achieved at the design point, through increasing the flow of control air, while maintaining a constant head rise. The peak efficiency of this combination was 83 percent. From this peak efficiency, achieved with a moderate amount of control air, the efficiency dropped to a low of 65 percent when operating with a maximum flow of control air. It is shown that the most likely demands of the heave alleviation system would allow for the fan to operate at the highest efficiency possible for the flow rate required.

The high solidity (σ = 1.3) impeller was found to produce an increase in flow rate of 50 percent over that achieved at the design point, through increased control air, and did not achieve as high an efficiency as that of the lower solidity configuration.

40. Wilkerson, J.B., "An Assessment of Circulation Control Airfoil Development," DTNSRDC Report 77-0084, AD A043-826 (Aug 1977).

A circulation control CC airfoil development program is presented, including an airfoil designation system. Specific performance objectives are set forth as development goals. Background information includes an assessment of state-of-the-art design practices, a comparison of operational requirements with those of conventional airfoils, and a discussion of previous airfoil performance. Selection and design criteria are described for five new CC airfoils. These designs were wind-tunnel evaluated as two-dimensional models. A limited amount of airfoil data is shown for comparison to the prior data base.

Two of the airfoils were designed with the objective of maintaining high lift augmentation and improving the critical Mach number characteristics, a combination of qualities that was previously nonexistent. Both designs theoretically accomplished the prescribed goals and were validated by experimental results. The development program has advanced the state of the art and nearly doubled the available data base for CC airfoils.

41. Hemmerly, R.A., "An Investigation of the Performance of a J-52-P-8A Engine Operating Under the Influence of High Bleed Flow Extraction Rates," DTNSRDC Report ASED-387, AD A057-325 (Aug 1977).

The uninstalled performance characteristics of a J-52-P-8A engine operating under the influence of bleed flow extraction rates in excess of the standard specification limits were experimentally evaluated. This investigation was undertaken as part of the Circulation Control Wing Flight Demonstrator Program to (1) assess the engine's capability of supplying airflow to power the STOL aerodynamic system incorporated on the flight demonstrator, and (2) to define a data base from which

higher confidence level analytical STOL performance evaluations could be obtained. Results of the investigation indicate that bleed flow extraction rates significantly greater than the standard specification limits are obtainable. An endurance evaluation of the engine operating under the influence of the high bleed flow extraction rate indicates that these extraction rates do not adversely affect the J-52-P-8A engine. The results of the endurance evaluation should qualify the J-52-P-8A engine for the proposed Flight Test Program.

42. Abramson, J., "Two-Dimensional Subsonic Wind Tunnel Evaluation of Two Related Cambered 15-Percent-Thick Circulation Control Airfoils," DTNSRDC Report ASED-373, AD A055-140 (Sep 1977).

Two circulation control cambered elliptic airfoil sections with a thickness-to-chord ratio of 0.15- and 1.0-percent circular arc camber were evaluated subsonically to determine their aerodynamic characteristics. The two models, designated NCCR 1510-7067N and NCCR 1510-7567S, have a common leading edge but different Coanda surfaces. Model NCCR 1510-7067N produced lift coefficients up to 4.65 at $C_\mu = 0.234$; $C_\ell = 4.03$ was attained by NCCR 1510-7567S at $C_\mu = 0.145$. Model NCCR 1510-7067N was limited in performance by a relatively sharp leading edge that resulted in leading edge separation. Coanda jet-tunnel floor interference, presumably due to effective Coanda turning occurs with model NCCR 1510-7067S at relatively low values of momentum coefficient thereby restricting the test range. Lift-to-equivalent drag ratios in excess of 40 are produced by both configurations at $C_\ell = 1.0$. The ability to produce relatively high lift coefficients essentially independent of angle of attack is indicated by the results of this investigation.

43. Wilkerson, J.B., "Static Stability Derivatives of a Model Circulation Control Rotor," DTNSRDC Report 77-0066, AD A046-710 (Oct 1977).

Static stability derivatives of a circulation control rotor (CCR) were obtained from wind tunnel evaluation of a model rotor. The derivatives show general characteristics similar to those of a conventional rotor in the advance ratio range $0.20 \leq \mu \leq 0.30$. The conventional characteristic of a destabilizing static-speed-stability term for hingeless rotors appears to be magnified for low advance ratios in the CCR system. At higher advance ratios the static-speed-stability term becomes neutral and then strongly stable for CCR. Other derivatives show the same tendency toward neutral stability as speed is increased beyond an advance ratio of 0.30. If this model trait is corroborated by future full-scale CCR evaluation, it will represent a significant advantage in stability characteristics over current hingeless rotors.

44. Reader, K.R., "The Effects of Cam and Nozzle Configuration on the Performance of a Circulation Control Rotor Pneumatic Valving System," DTNSRDC Report ASED-393, AD A050-494 (Nov 1977).

Basic research was conducted on the sensitivity of such component parts of a cam-type pneumatic valving system as cam eccentricity, nozzle aspect ratio, nozzle shape, nozzle endplates, slot exit area, and transition zone between the nozzle and blade entrance. Data are presented which show how systematic variations of these components affect the total pressure loss coefficient, the mass flow rate, and the jet velocity. Information on the sensitivity of these parameters enhances the capabilities to design a cam-type pneumatic valve.

It was concluded that cam eccentricity has no effect on the characteristic curve for total pressure loss coefficient versus area coefficient. Accordingly, no stringent requirement should be encountered in changing the cross-sectional shape for the size of the nozzle. Streamlining of the transition section between the nozzle and blade entrance did not affect the pressure recovery in the operational range of the valve nor the shape or the harmonic content of the loss coefficient or mass flow rate curves. The addition of endplates to the nozzle reduced the total pressure losses between the hub and the blade.

The area coefficient and total pressure loss coefficient are shown to be adequate parameters to correlate the data for different valve models.

45. Englar, R.J., "Development of the A-6/Circulation Control Wing Flight Demonstrator Configuration," Report DTNSRDC/ASED-79/01, AD A081-241 (Jan 1978).

Wind tunnel investigations were conducted on a 1/8.5-scale model of the A-6/Circulation Control Wing flight demonstrator aircraft in order to confirm the high lift capability of the concept, to improve lifting and control surfaces and to provide supporting data to assure safety of flight and adequate handling of the full-scale aircraft. The best configuration developed during these investigations produced a 2.2-fold increase in $C_{L_{max}}$ over the conventional A-6A high lift configuration. This CCW configuration was compromised to simplify testbed aircraft modifications, reduce construction costs, and provide a larger range of parameters obtainable during flight testing, yet in the final configuration, still provided trimmed aerodynamic $C_{L_{max}}$ double that of the standard A-6A. Additional studies included: Reynolds number and slot height variations, operation in ground effect, stall and stall hysteresis, effect of lifting surface imperfection, additional drag generators, flow field at the tail surface, and longitudinal stability levels with aft c.g. shift. Data from the present studies should provide an adequate base upon which to construct the full-scale flight demonstrator and predict its STOL performance and longitudinal flying qualities.

46. Englar, R.J., L.A. Trobaugh, and R.A. Hemmerly, "STOL Potential of the Circulation Control Wing for High-Performance Aircraft," J. of Aircraft, Vol. 15, No. 3 (Mar 1978).

Research and development being conducted at the David Taylor Naval Ship R&D Center investigates the STOL capability of the Circulation Control Wing (CCW) concept on high-performance aircraft. This high-lift system, which employs tangential blowing over a rounded trailing edge and requires mass flows characteristic of state-of-the-art turbine engine bleed, has demonstrated the ability to more than double the lift capability of conventional Navy and Marine aircraft. The resulting reduced takeoff and landing speeds and distances, plus increased overload capability, are achieved without severe compromise of wing structure, weight, or engine arrangement, and without large quantities of ducted hot gas. Based on these anticipated benefits and the results of existing experimental investigations, a program has been initiated to demonstrate the STOL capability of the CCW concept applied to a full-scale A-6 flight demonstrator aircraft. This paper will address the experimental development and optimization of the CCW system on an A-6 model and will present predicted full-scale STOL performance gains for the flight demonstrator.

47. Englar, R.J., "Characteristics and Development of the Circulation Control Airfoil," Proceedings of Advanced Technology Airfoil Research Conference, NASA Conf. Publication 2046, Hampton, Virginia (7-9 Mar 1978).

The Circulation Control airfoil, a promising concept in blown aerodynamics, has been under development and has exhibited a number of unique aerodynamic properties. This concept employs tangential blowing from a thin upper surface slot over the airfoil's rounded trailing edge. The jet sheet remains attached to and turns around the trailing edge, thus controlling the circulation around the airfoil. Experimental results are presented for numerous airfoils of this type which show high lift augmentation and lift coefficients exceeding those predicted for inviscid flow. Benefits of the CC airfoil thus include high lift from low values of momentum (blowing) coefficient, lift essentially independent of airfoil incidence, and equivalent aerodynamic efficiencies on the same order as conventional unblown airfoils but at considerably higher lift coefficient. These primary characteristics have led to three ongoing full scale flight demonstration programs: a STOL fixed wing aircraft, an advanced rotary wing vehicle, and a combination fixed wing-rotary wing V/STOL aircraft. The CC airfoil has also been applied experimentally as a water-blowing control surface for submarines, blades in a lifting fan for a surface effect vehicle, and as a transonic rotor tip section. The present paper describes and presents the characteristics and operation of these airfoils, experimental results, comparison to theoretical predictions, and ongoing development leading to advanced versions of the CC airfoil.

48. Reader, K.R., D.G. Kirkpatrick, and R.M. Williams, "Status Report on Advanced Development Program Utilizing Circulation Control Rotor Technology," Paper No. 44 presented at Fourth European Rotorcraft and Powered Lift Aircraft Forum, Stresa, Italy (13-15 Sep 1978).

The current status of circulation control aerodynamics research and of two full scale flight demonstrator aircraft development programs, employing circulation control rotors, is presented. The development of circulation control technology has taken an orderly progression from two-dimensional airfoil experiments and analytical studies through three-dimensional subscale rotor experiments and correlation to full scale rotor development and flight tests. The first program, the Circulation Control Rotor (CCR), includes the installation of a conventional speed circulation control rotor on an exisitng H-2D airframe. This development is being pursued under U.S. Navy contract to Kaman Aerospace Corporation, Bloomfield, Connecticut. The second program consists of the development of a new VTOL aircraft, the stopped rotor X-Wing. This flight demonstrator is being developed under DARPA (Defense Advanced Research Projects Agency) contract to Lockheed Aircraft Corporation, Burbank, California. Both of these programs are scheduled to be tested in the NASA Ames 12 × 24 m (40 × 80 ft) wind tunnel during late 1978.

In-house laboratory research programs leading to the translation of CCR and X-Wing technologies into industry are described. Current status of the CCR design, fabrication and initial whirl stand validation efforts, in preparation for the July 1978 tests in the Ames tunnel, are described. Plans call for testing the flight vehicle early in 1979. Also described are the results of a preliminary design study and hardware fabrication program for the X-Wing. The X-Wing rotor is to be extensively tested on the whirl stand in preparation for NASA wind tunnel tests around September 1978. The results of current theoretical and experimental analyses of all flight modes of both the CCR and the X-Wing show that no fundamentally limiting problems exist at the present stage of development.

49. Englar, R.J., "STOL—The Potential of the Circulation Control Wing Concept," Naval Engineers J. (Apr 1979).

In order to develop advanced aricraft for operation from smaller air-capable ships, research and development are being conducted at the David W. Taylor Naval Ship Research and Development Center to investigate the Short Takeoff and Landing (STOL) capability of the Circulation Control Wing concept. This high lift system employs tangential blowing over the rounded wing trailing edge, and can more than double the lifting capability of conventional high performance aircraft. The resulting reduced takeoff and landing speeds and distances can produce a significant favorable impact on the design of future aircraft-carrying ships and operations from these vessels. Based on these promising benefits, a program is underway to demonstrate the STOL capability of the concept applied to a full-scale A-6 flight demonstrator aircraft. The present paper addresses experimental development of this vehicle, details of the full-scale aircraft modifications, and predicted STOL performance benefits for future sea-based aircraft so equipped.

50. Abramson, J. "The Low-Speed Characteristics of a 15-Percent Quasi-Elliptical Circulation Control Airfoil with Distributed Camber," Report DTNSRDC/ASED-79/07, AD A084-176 (May 1979).

The aerodynamic characteristics of a circulation control elliptic airfoil section with a 15-percent thickness-to-chord ratio were evaluated subsonically. The airfoil, designated NCCR1513-7559E, incorporates a high degree of nose camber and an increased leading edge radius in a profile designed for high subsonic speeds. Critical Mach numbers in excess of 0.7 were predicted analytically for several typical operating conditions. Lift coefficients up to 4.63 were produced at momentum coefficients of 0.22. Equivalent lift-to-drag ratios of approximately 40 were also produced at $C_\ell = 0.8$.

51. Wilkerson, J.B., D.R. Barnes, and R.A. Bill, "The Circulation Control Rotor Flight Demonstrator Test Program," Paper 79-51 presented at 35th Annual National Forum of American Helicopter Society, Washington, D.C. (May 1979).

The circulation control rotor (CCR) technology demonstrator, XH-2/CCR, has undergone many phases of structural, pneumatic, and aerodynamic tests, leading to the flight demonstration. A description of XH-2/CCR is provided with brief descriptions of the major tests conducted. Results of pneumodynamic tests of the compressor and control system are presented. Emphasis is placed on performance results from the whirl stand and from the NASA Ames 40- by 80-foot wind tunnel. Correlation between wind tunnel data and theory is also shown. A good agreement was evident over the flight spectrum for the first full-scale CCR.

52. Prince, S.W., "Experimental Investigation of a Circulation Control Aileron, Report DTNSRDC/ASED-79/08, AD A078-825 (Jul 1979).

A Circulation Control (CC) aileron was tested on a semispan wing-fuselage model at a dynamic pressure equal to 20 lb/ft^2 (957 N/m^2) and a Reynolds number of $0.8 \times 10^6/ft$ ($2.62 \times 10^6/m$). Three different trailing edge geometries were used on CC ailerons of 10 and 20 percent of the half span. Blowing was controlled to produce jet momentum coefficients from 0.0017 to 0.0124. Rolling moment coefficients as high as 0.035 were recorded for the 20-percent CC aileron for angles of attack between 0 and 12 deg. The CC aileron was at least three times as effective as a pure reaction jet for the same amount of bleed air. Adverse yaw was large, on the order of one-half of the rolling moment.

53. Englar, R.J. et al., "Design of the Circulation Control Wing STOL Demonstrator Aircraft," AIAA Paper 79-1842 presented at AIAA Aircraft Systems and Technology Meeting, New York (20-22 Aug 1979).

Research and development have been conducted at the David W. Taylor Naval Ship R&D Center to develop the STOL capability of the Circulation Control Wing concept. This simple high lift system employs tangential blowing over the wing's rounded trailing edge, and can more than double the lifting capability of conventional high performance aircraft. Based on the associated STOL benefits, design and flight testing of the concept on a full-scale A-6A flight demonstrator have been completed by Grumman Aerospace Corporation. The present paper addresses experimental development of the vehicle, details of the full-scale aircraft design, predicted STOL performance benefits, and some flight test results.

54. Pugliese, A.J. (Grumman Aerospace Corp.) and R.J. Englar (DTNSRDC), "Flight Testing the Circulation Control Wing," Paper AIAA-79-1791 presented at AIAA Aircraft Systems and Technology Meeting, New York (20-22 Aug 1979).

The Grumman A-6A was modified and flight tested to demonstrate the high lift and STOL capability of the Circulation Control Wing (CCW) concept, which employs a circular trailing edge blown by engine bleed air. The test program included a ground test series for calibration, adjustment, and checkout of the blowing system, followed by a limited duration flight program to measure blown lift enhancement and resulting STOL improvements. The paper describes the test program, emphasizing flight safety considerations and application of recently developed flight test techniques to accomplish the program's optimistic objectives. Test results are discussed, including the successful demonstration of lift augmentation and significant STOL performance.

55. Reader, K.R., "The Effect of Shaft Angle on Performance of a Circulation Control High-Speed Rotor at an Advance Ratio of 0.7," Report DTNSRDC-80/015, AD A080-953 (Feb 1980).

As part of the on-going Circulation Control Rotor Technology Program at the David W. Taylor Naval Ship Research and Development Center, a high-speed rotor model designated the Reverse Blowing Circulation Control Rotor (RBCCR) was evaluated in a wind tunnel in the forward flight mode. The RBCCR model was used to evaluate the effects of rotor shaft angle of attack on rotor performance at the transitional advance rate of $\mu = 0.7$. The test variable included rotor thrust, blade collective pitch angle, tip Mach number, and rotor shaft angle. Major findings are summarized as follows:

1. Rotor performance has been shown to improve by a substantial amount as shaft angle increases from -5 to +2.5 degrees.

2. The rotor experiences better thrust augmentation at a fixed blade collective pitch angle as shaft angle increases. The increased thrust augmentation results in better rotor efficiencies with increasing shaft angle.

3. A trim limit relationship between shaft angle and blade collective pitch angle has been established to be $\theta_c = -0.5647\ \alpha_s - 0.7$.

4. As the shaft angle is varied, a trade-off exists between shaft power and compressor power over a range of thrust.

The RBCCR model has demonstrated both the lift and trim capabilities required in the transitional flight regime. The model has also shown that rotor efficiency and power sharing between shaft power and compressor power can be controlled by rotor shaft angle at an advance ratio of 0.7.

56. Nichols, J.H., Jr., "Development of High Lift Devices for Application to Advanced Navy Aircraft," Report DTNSRDC-80/058, AD A084-226 (Apr 1980).

A number of methods for generating high lift to provide a short takeoff and landing (STOL) capability for advanced Navy aircraft are evaluated, with emphasis on low aspect ratio wings. Upper surface blowing, circulation control wing, and wing tip sails are given the most attention. Experimental data are being obtained in the DTNSRDC wind tunnels on these concepts as specifically applied to wings of aspect ratios 3 to 5. Flight demonstrations by Grumman and DTNSRDC of a circulation control wing application to the A-6 aircraft have shown the ability to more than double the lifting capability which resulted in landing speed reductions of more than 30 percent, landing ground roll reductions of more than 50 percent, and takeoff distance reductions of at least 25 percent. The experimental high lift system data have been applied to a conceptual STOL baseline aircraft in order to estimate the impact on mission performance and identify their various merits as applicable to the particular restrictions of small ship operations.

57. Trobaugh, L.A., D.G. Lee, and M.J. Harris, "Low Speed Aerodynamic Characteristics of Wings of Aspect Ratios 3 and 4 Equipped with High Lift Systems," Report DTNSRDC/ASED-80/09, AD A087-768 (May 1980).

Low speed wind tunnel data show that wings of aspect ratios 3 and 4 can produce maximum lift coefficients twice that of conventional double-slotted flap configurations by using powered high lift systems. These high lift systems, which utilize either the circulation control or upper surface blowing concepts, were applied to a semispan wing-fuselage model having a supercritical airfoil section.

58. Furey, R.J., "High Lift Capability of Low Aspect Ratio Wings Utilizing Circulation Control and Upper Surface Blowing," Report DTNSRDC/ASED-80/15, AD A112-312 (Jul 1980).

A semispan research model with a 2-ft span wing was used to measure the high lift capabilities of low aspect ratio wings utilizing powered-lift concepts. The concepts evaluated were the Circulation Control Wing (CCW), the Upper Surface Blowing (USB), and a unique combination of the two (CCW/USB). Wing tip sails were used as a means of increasing the effective aspect ratio of these wings during high lift.

59. Chaplin, H.R., "Some Dynamic Properties of a Rigid Two-Bladed Fully Gimballed Tip-Jet Helicopter Rotor with Circulation Control," Report DTNSRDC/TM-16-80/16 (Aug 1980).

Simplified analyses are carried out for the motions of a simple rigid two-bladed fully gimballed rectangular rotor rotating at constant speed about a stationary center point and about a center point translating at a low constant advance ratio. (The term "fully gimballed" means that hub moments about all axes are zero.) It is conluded that:

1. The rotor can be rendered dynamically stable by appropriate mass balancing. In a particular example considered, the mass balancing was estimated to increase the rotor weight by about 20%.
2. The steady state motion about a translating center due to first harmonic moments induced by translation is a wobbling motion with the principal axis of rotation describing a cone about its mean position at twice the rotor rotational frequency.
3. A circulation control system can control total rotor lift and can cause precession of the mean position of the principal rotational axis to any desired orientation. It cannot, however, influence the amplitude of the steady state wobble.
4. Over a range of flight conditions practical for a large crane-type helicopter, the maximum amplitude of steady state wobble is estimated to be on the order of 3 degrees or less. (It can be made quite small by designing to carry most of the average lift in the form of circulation-control-induced lift and camber-induced lift.)

60. Nichols, J.H., Jr., and R.J. Englar, "Advanced Circulation Control Wing System for Navy STOL Aircraft," Paper AIAA-80-1825 presented at AIAA Aircraft Systems Meeting, Anaheim, California (4-6 Aug 1980).

An advanced high lift system is being developed which combines a circulation control wing (CCW) with upper surface blowing (USB) to produce significant lift for STOL operations by Navy aircraft. The concept uses circulation control (CC) to pneumatically deflect USB engine thrust and thus augment aerodynamic wing lift

produced by the outboard CCW. Wind tunnel investigations have confirmed significant thrust turning to angles near 165 deg, providing a simple, highly effective STOL and thrust reverser system. A no-moving-parts VTOL system obtained by deflecting thrust to angles around 90 deg is also suggested. The paper presents experimental results, a conceptual design for a proposed CCW + CC/USB STOL aircraft, and predicted STOL characteristics for that aircraft. Payoff in aircraft mechanical simplicity is also discussed.

61. Montana, P.S., "Lift-Propulsion System Weight Variation for Very Heavy Lift Helicopters," Report DTNSRDC/ASED-80/25, AD A099-169 (Sep 1980).

The lift-propulsion system (LPS) weights of single and tandem rotor shaft-driven helicopters and single rotor tip-driven helicopers were estimated using weight trend equations for vehicle gross weights up to 250,000 lb (113,636 kg). The tip-driven helicopter configuration had the lowest LPS weight over the entire gross weight range and the greatest potential for achieving useful loads in excess of 60,000 lb (27,216 kg). Results of the sensitivity analysis indicate that disc loading, number of blades, and solidity of the main rotor are the most significant parameters affecting LPS weight. The application of circulation control rotor technology to very large helicopters with tip-driven rotors can reduce LPS weight by as much as 19 percent.

62. Rogers, E.O., "Recent Progress in Performance Prediction of High Advance Ratio Circulation Controlled Rotors," Paper No. 29 presented at Sixth European Rotorcraft and Powered Lift Aircraft Forum, Bristol, England (16-19 Sep 1980).

The application of circulation control technology to rotors adds several new aerodynamic parameters to the design process and will permit expanded operating regimes for rotorcraft. High advance ratio (0.5 to 0.7) lifting rotor operation is characterized by highly nonuniform blade loading distributions, wake skew angles within a few degrees of the plane of rotation, and strong blade/vortex encounters. The development and validation of analytical procedures for the above conditions are essential to fully exploit advanced concepts such as the X-Wing VTOL aircraft. Accordingly, an extensive subscale rotor data base was used to develop a new, high advance ratio performance methodology. One major factor in the success achieved so far has been the use of a vortex wake inflow computer code. At all advance ratios examined (0.3 to 0.7), correct prediction of experimental roll moment and thrust resulted only when the vortex-based inflow theory was used. With the inflow field represented in this manner, the extensive circulation control airfoil data base, corrected appropriately for local flow conditions, can be applied in a classical quasi-steady blade element approach to rotor performance prediction. In related experimental investigations, flow visualization (tufts) at 0.7 advance ratio has confirmed the suppression of separated flow by simultaneous leading and trailing edge blowing on the retreating side. The potential of higher harmonic pneumatic control has also been demonstrated by the virtual elimination of the twice-per-revolution blade flatwise moment.

63. Poe, D.W., "Design of a Slot Height Distribution for Increased Hover Control Power on a Circulation Control Rotor," Report DTNSRDC/ASED-80/24, AD A103-535 (Dec 1980).

The Circulation Control Rotor Performance Prediction computer program was used with the XH-2/CCR rotor configuration to determine a slot height distribution that would improve control power in hover without causing excessive cyclic pressure requirements for trim in forward flight. Effects of total slot area as well as distribution were considered. The final distribution was constrained by a minimum practical slot height setting of 0.002 in. and a minimum unpressurized blade slot area of 3.0 in^2. Several distributions were evaluated. Noteworthy trends that emerged are: (1) A negatively tapered slot height distribution is favorable to producing hub moments in hover, and (2) a uniform distribution (zero taper) requires the lowest cyclic pressure for trim at 120 knots. The final distribution selection exhibited a 38-percent improvement in predicted hub moment over a slot height distribution previously used on the flight demonstrator.

64. Englar, R.J. et al., "Design of the Circulation Control Wing STOL Demonstrator Aircraft," AIAA-79-1842R, J. of Aircraft, Vol. 18, No. 1 (Jan 1981).

Research and development have been conducted at the David W. Taylor Naval Ship Research and Development Center to develop the STOL capability of the circulation control wing concept. This simple high lift system employs tangential blowing over the wing's rounded training edge, and can more than double the lifting capability of conventional high performance aircraft. Based on the associated STOL benefits, design and flight testing of the concept on a full-scale A-6A flight demonstrator have been completed by Grumman Aerospace Corporation. The present paper addresses experimental development of the vehicle, details of the full-scale aircraft design, predicted STOL performance benefits, and some flight test results.

65. Nichols, J.H., Jr., et al., "Experimental Development of an Advanced Circulation Control Wing System for Navy STOL Aircraft," Paper AIAA-81-0151 presented at AIAA 19th Aerospace Sciences Meeting, St. Louis, Missouri (12-19 Jan 1981).

An advanced high lift system is being developed which combines a Circulation Control Wing (CCW) with Upper Surface Blowing (USB) to produce significant lift for STOL operations by Navy aircraft. The concept uses circulation control to pneumatically deflect USB engine thrust and thus augment aerodynamic wing lift produced by the outboard CCW. Two series of wind tunnel investigations have confirmed significant thrust turning to angles near 160°, suggesting the possibility for a simple, highly effective STOL and thrust reverser system. Two-dimensional investigations of reduced diameter CCW trailing edges suggest their application as a no-moving-parts high lift system with minimal cruise penalty. The paper presents these experimental results and summarizes the technology development progressing towards an advanced STOL aircraft.

66. Tai, T.C. and G.H Kidwell, Jr., "Numerical Optimization of Circulation Control Airfoils," Paper AIAA-81-0016 presented at AIAA 19th Aerospace Sciences Meeting, St. Louis, Missouri (12-15 Jan 1981).

A numerical procedure for optimizing circulation control airfoils, which consists of the coupling of an optimization scheme with a viscous potential flow analysis for blowing jet, is presented. The desired airfoil is defined by a combination of three baseline shapes (cambered ellipse, and cambered ellipse with drooped and spiralled trailing edges). The coefficients of these shapes are used as design variables in the optimization process. Under the constraints of lift augmentation and lift-to-drag ratios, the optimal airfoils are found to lie between those of cambered ellipse and the drooped trailing edge, towards the latter as the angle of attack increases. Results agree qualitatively with available experimental data.

67. Englar, R.J., "Low-Speed Aerodynamic Characteristics of a Small Fixed-Trailing-Edge Circulation Control Wing Configuration Fitted to a Supercritical Airfoil," Report DTNSRDC/ASED-81/08, AD A101-540 (Mar 1981).

Excellent high-lift and cruise performance of a small, round, fixed circulation control wing (CCW) trailing edge fitted to a supercritical airfoil has been confirmed by subsonic wind tunnel investigations. This fixed-trailing-edge blown high-lift airfoil generates a negligible subsonic cruise drag penalty, but can generate a section lift coefficient near 7.0. This configuration is a significant improvement over the flight-proven A-6/CCW airfoil that had similar lift performance, but had a large trailing edge requiring mechanization for transition to cruise flight. Further, the large leading edge radius of the supercritical airfoil allows operating at high lift over a moderate angle-of-attack range. These results imply the feasibility of a mono-element airfoil with no moving components required for high lift; the transition from the cruise to the high-lift configuration is accomplished by blowing from a fixed slot. The favorable characteristics of both the cruise and high-lift airfoils are retained without compromise to either.

68. Head, R.E. (Hughes Helicopters, Inc.), "Preliminary Design of a Tip-Jet-Driven Heavy Lift Helicopter Incorporating Circulation Control," Report DTNSRDC/ASED-81/07, AD A099-192 (Mar 1981).

This report describes a preliminary design study for a Very Heavy Lift Helicopter (VHLH) that is powered by jets at the blade tips and is controlled by circulation control applied to the main rotor blades. The main thrust of the program was to integrate a tip-jet-powered helicopter design computer program developed by Hughes Helicopters, Inc. (HHI) with circulation control data generated by the David Taylor Naval Ship Research and Development Center (DTNSRDC). This work, which was conducted under Navy contract N00167-80-C-0066, combined the computer program integration work with an air vehicle preliminary design study to size the helicopter and describe its features. The result of this study is the sizing of a

four-engined helicopter with a 185-foot-diameter, two-bladed main rotor that is designed to carry the XM-1 Main Battle Tank 100 nautical miles in a ship-to-shore Marine Corps assault mission.

69. Tai, T.C., "The Determination of Drag of a Circulation Control Airfoil Tested in the 7- by 10-Foot Transonic Wind Tunnel," Paper presented at 55th Semi-annual Meeting of Supersonic Tunnel Association, Amsterdam, The Netherlands (27-29 Apr 1981).

A special procedure for using the Jones method for determining the profile drag in highly disturbed wake behind a circulation control airfoil is proposed. The procedure suggests that the value of the freestream dynamic pressure be adjusted so that the baseline of the integrand in the Jones method coincides with the zero reference line. Excellent agreement was observed between the results of the new procedure and those of the simultaneous solution values of the Jones and the Squire-Young methods.

70. Harris, M.J., "Investigation of the Circulation Control Wing/Upper Surface Blowing High-Lift System on a Low Aspect Ratio Semispan Model," Report DTNSRDC/ASED-81/10, AD A103-090 (May 1981).

The results from one in a series of investigations undertaken to develop the Circulation Control Wing/Upper Surface Blowing (CCW/USB) high-lift concept are presented. Included are: isolation of propulsion jet turning, effects of tip devices, and thrust reversing. As evaluated, the concept employs a modified supercritical wing with a 3.6-percent chord circular trailing edge and tangential blowing from a thin, full-span slot over this trailing edge. In addition, turbofans are mounted over the wing so that the exhaust scrubs the upper surface of the wing and is turned by the trailing edge. Unlike other upper surface blowing concepts, thrust deflection is accomplished by entraining the propulsive jet with tangential blowing around the trailing edge. The propulsive-induced lift enhances the proven high lift of the circulation control wing. For a thrust coefficient of 3.76, a tangential blowing coefficient of 0.24, and an angle of attack of 16 deg, the low aspect ratio model produced an untrimmed lift coefficient of 6.5. The system also demonstrated the capability to be used as an effective thrust reverser for deceleration during the landing ground roll.

71. Nichols, J.H., Jr., et al., "Experimental Development of an Advanced Circulation Control Wing System for Navy STOL Aircraft," Report DTNSRDC-81/045, AD A101-309 (May 1981).

An advanced high lift system is being developed which combines a Circulation Control Wing (CCW) with Upper Surface Blowing (USB) to produce significant lift for STOL operations by Navy aircraft. The concept uses circulation control to pneumatically deflect USB engine thrust and thus augment aerodynamic wing lift produced

by the outboard CCW. Two series of wind tunnel investigations have confirmed significant thrust turning to angles near 160 deg, suggesting the possibility for a simple, highly effective STOL and thrust reverser system. Two-dimensional investigations of reduced diameter CCW trailing edges suggest their application as a no-moving-parts high lift system with minimal cruise penalty. The paper presents these experimental results and summarizes the technology development progressing towards an advanced STOL aircraft.

72. Abramson, J. and E.O. Rogers, "Optimization Theory Applied to Higher Harmonic Control of Circulation Controlled Rotors," Paper No. 81-3 presented at 37th Annual Forum of American Helicopter Society, New Orleans, Louisiana (17-20 May 1981); also published in Vertica, Vol. 6 (1982).

The feasibility of using numerical optimization techniques to determine control inputs to a high speed rotor system employing circulation control aerodynamics was investigated. The objective was to determine the azimuthal loading distribution (cyclic pressure waveform) which would be optimum with respect to performance parameters such as compressor power, mass flow, or peak cyclic pressure. An optimization code, COPES/CONMIN, is coupled with an empirically derived model of the rotor based on cyclic control perturbation derivatives. For specific flight conditions, solutions were obtained for optimum cyclic waveforms. These control inputs were experimentally verified, producing up to a 20 percent reduction in compressor power as compared to the standard one-per-revolution cyclic control. Influences on blade loading are presented along with investigations of blade response to higher harmonic control inputs. The mathematical concepts and procedures used should be applicable to conventional (unblown) rotors.

73. Englar, R.J., "Development of the CCW/Supercritical No-Moving-Parts High Lift Airfoil," Presented at AFSC/NAVMAT Science and Engineering Symposium, Wright-Patterson AFB, Ohio (27-29 Oct 1981).

Excellent high-lift and cruise performance of a small, round, fixed circulation control wing (CCW) trailing edge integrated into a supercritical airfoil have been confirmed by subsonic wind tunnel investigations. This fixed-trailing-edge, blown high lift airfoil can generate a section lift coefficient near 7.0 when blowing is activated, but generates a negligible unblown subsonic cruise drag penalty relative to the conventional airfoil. This configuration is a significant improvement over the flight-proven A-6/CCW STOL demonstrator airfoil that had similar lift performance, but had a large trailing edge which would require mechanization for transition to cruise flight. Further, the large leading edge radius of the supercritical airfoil allows operation at high lift over an angle-of-attack range without any mechanical leading edge device. These results imply the feasibility of a monoelement airfoil with no moving components required for high lift. The transition from the cruise to the high-lift configuration is accomplished by blowing from a fixed slot, and the favorable characteristics of both airfoils are retained without compromise to either. This combined CCW/Supercritical airfoil can provide very significant

STOL or heavy lift capabilities for both military and commercial aircraft, while its mechanical simplicity promises reductions in high lift system weight and complexity. The paper will present experimental results of the airfoil development program and discuss possible applications.

74. Nichols, J.H., Jr., and R.J. Englar, "Advanced Circulation Control Wing System for Navy STOL Aircraft," AIAA-80-1825R, J. of Aircraft, Vol. 18, No. 12 (Dec 1981).

An advanced high lift system is being developed which combines a circulation control wing (CCW) with upper surface blowing (USB) to produce significant lift for STOL operations by Navy aircraft. The concept uses circulation control (CC) to pneumatically deflect USB engine thrust and thus augment aerodynamic wing lift produced by the outboard CCW. Wind tunnel investigations have confirmed significant thrust turning to angles near 165 deg, providing a simple, highly effective STOL and thrust reverser system. A no-moving-parts VTOL system obtained by deflecting thrust to angles around 90 deg is also suggested. The paper presents experimental results, a conceptual design for a proposed CCW + CC/USB STOL aircraft, and predicted STOL characteristics for that aircraft. Payoff in aircraft mechanical simplicity is also discussed.

75. Tai, T.C. and G.H. Kidwell, Jr., "Numerical Optimization of Circulation Control Airfoils," AIAA-81-0016R, J. of Aircraft, Vol. 19, No. 2 (Feb 1982).

A numerical procedure for optimizing circulation control airfoils, which consists of the coupling of an optimization scheme with a viscous-potential flow analysis for blowing jet, is presented. Without losing the generality of the methodology, special attention is given to optimizing the blunt trailing edge, which has a direct bearing on the jet deflection characteristics. The desired airfoil is defined by a combination of three baseline shapes: cambered ellipse, cambered ellipse with drooped trailing edge, and cambered ellipse with spiraled trailing edge. The coefficients of these shapes are used as design variables in the optimization process. Under the constraints of lift augmentation and lift-to-drag ratios, the optimal airfoils are found to lie between those of the cambered ellipse and the drooped trailing edge, toward the latter as the angle of attack increases. Results agree qualitatively with the available experimental data.

76. Wilkerson, J.B. and P.S. Montana, "Transonic Wind Tunnel Test of a 16-Percent-Thick Circulation Control Airfoil with One-Percent Asymmetric Camber," Report DTNSRDC/ASED-82/03, AD A116-298 (Apr 1982).

A two-dimensional circulation control (CC) airfoil model was tested in the 7- by 10-foot transonic wind tunnel at the David W. Taylor Naval Ship R&D Center. Test conditions covered a range of free-stream Mach numbers (0.3 to 0.8), angles of attack (-10 to +6 deg), and blown jet pressure ratios (0 to 3.0). These data provided the first information on the influence of angle of attack on CC airfoil drag and lift

augmentation at transonic speeds. The tested CC airfoil NCCR 1610-8054S was quasi-elliptical in shape, having a 16-percent thickness to chord ratio, with 1-percent maximum camber occurring at 70-percent chord. The program objectives were to achieve improved performance at transonic speeds while maintaining the characteristically high-lift augmentation at low subsonic operation. These objectives required nonsymmetrical thickness and camber distributions for the airfoil. Performance goals were qualitatively substantiated by the transonic test data. At 2-deg angle of attack, a maximum lift coefficient of 2.1 was obtained at $M_\infty = 0.3$; while for $M_\infty = 0.6$ at the same angle, the maximum lift coefficient was 0.76. As a high-lift device the airfoil was very effective at and below $M_\infty = 0.4$. As a means of direct lift control the airfoil remained effective up through $M_\infty = 0.7$.

77. Kuhn, R.E., "High Pressure Bleed for STOL and STO-VL Performance--A Conceptual Examination," Report DTNSRDC-82/032, AD A115-762 (May 1982).

The engines in modern combat aircraft are sized by combat maneuverability considerations. These aircraft therefore have much more thrust available than is needed at normal takeoff and landing speeds. Only the Harrier, which can vector the thrust of the centrally-mounted engine through the center of gravity can use its excess thrust to reduce the takeoff and landing distance (to zero at low operating weights). The engines on the others are too far aft for direct thrust vectoring. This paper examines other possibilities. The main emphasis is on the possibility of using bleed air from the high pressure compressor to blow the wing and/or a canard for STOL performance. Alternately, the use of this high pressure bleed to drive fold-out fans to achieve STO-VL performance is also examined.

78. Wellman, L.K. and C. Jacobsen, "Wind Tunnel Investigation of the Application of Circulation Control to a Forward Swept Wing," Report DTNSRDC/ASED-82/05, AD 068-714 (Jun 1982).

A wind tunnel investigation was conducted on a 0.285-scale forward swept wing (FSW) model using Circulation Control Wing (CCW) technology. The model was of the Rockwell International FSW flight demonstrator design. The investigation was conducted to verify that the pitching moment generated with circulation control can be reduced on a forward swept wing as compared with an aft swept wing. Aft swept CCW configurations are hampered by large pitch down moments as blowing is increased; consequently, the potential for improvement in aircraft high-lift performance is reduced by the trim requirements. With the circulation control forward swept wing design having a leading edge sweep angle of 40 degrees forward, additional moments generated at the quarter chord by CCW are reduced considerably and result in no additional moments to trim during CCW operations.

79. Eppel, J.C. et al. (NASA) and R.J. Englar and J.H. Nichols, Jr. (DTNSRDC), "Static Investigation of the Circulation-Control-Wing/Upper-Surface-Blowing Concept Applied to the Quiet Short-Haul Research Aircraft," Report NASA-TM-84232 (Jul 1982).

Full-scale static investigations have been conducted on the Quiet Short-Haul Research Aircraft (QSRA) to determine the thrust-deflecting capabilities of the circulation-control-wing/upper-surface-blowing (CCW/USB) concept. This scheme, which combines favorable characteristics of both the A-6/CCW and QSRA, employs the flow-entrainment properties of CCW to pneumatically deflect engine thrust in lieu of the mechanical USB-flap system. Results show that the no-moving-parts blown system produced static thrust deflections in the range of 40°-97° (depending on thrust level) with a CCW pressure of 2.089×10^5 Pa (30.3 psig). In addition, the ability to vary horizontal forces from thrust to drag while maintaining a constant vertical (or lift) value was demonstrated by varying the blowing pressure. The versatility of the CCW/USB system, if applied to a STOL aircraft, was confirmed, where rapid conversion from a high-drag approach mode to a thrust-recovering waveoff or takeoff configuration could be achieved by nearly instantaneous blowing-pressure variation.

80. Yang, H.S.D. (Lockheed-CA) and J.H. Nichols, Jr. (DTNSRDC), "Design Integration of CCW/USB for a Sea-Based Aircraft," Paper ICAS-82-1.6.1 presented at 13th Congress of International Council of the Aeronautical Sciences, AIAA Aircraft Systems and Technology Conference, Seattle, Washington (22-27 Aug 1982).

A design study is being conducted to apply the technologies of Circulation Control Wing with Upper Surface Blowing (CCW/USB) engine installation to a Navy/Lockheed sea based aircraft. Research and development in the CCW and USB concepts indicate that the application of the combined technologies may achieve a goal of operating the S-3 type aircraft from a ship deck without the catapult. The design emphasizes the integration of the propulsion system with a simple installation to obtain high lift or drag when required. Attention is also being directed to the cruise efficiency and the optimum design approach for stability and control.

81. Harris, M.J. et al., "Development of the Circulation Control Wing/Upper Surface Blowing Powered-Lift System for STOL Aircraft," Paper ICAS-82-6.5.1 presented at 13th Congress of the International Council of the Aeronautical Sciences, AIAA Aircraft Systems and Technology Conference, Seattle, Washington (22-27 Aug 1982).

The Circulation Control Wing/Upper Surface Blowing system is an advanced powered-lift concept currently under development for commercial and military application. High lift is generated by this system through pneumatic control of wing circulation and pneumatic deflection of jet engine exhaust. This potential to generate high lift as required for STOL operation has been confirmed through a

series of static and wind tunnel investigations. Static investigations included both small-scale cold gas and full-scale hot gas demonstrations. These investigations have demonstrated that this mechanically simple pneumatic system can generate high lift as effectively as heavier, complex mechanical flap systems. This paper summarizes the technology development of this advanced powered-lift system.

82. Englar, R.J., "Development of an Advanced No-Moving-Parts High-Lift Airfoil," Paper ICAS-82-6.5.4 presented at 13th Congress of the International Council of the Aeronautical Sciences, AIAA Aircraft Systems and Technology Conference, Seattle, Washington (22-27 Aug 1982).

An advanced Circulation Control Wing (CCW) airfoil has been developed by incorporating a very small radius blown trailing edge into the aft profile of an existing supercritical airfoil. This combined no-moving-parts configuration generates the same high lift as the already flight-proven large-radius CCW airfoils (section lift coefficient near 7), yet produces negligible unblown drag penalty due to leaving the device deployed for cruise flight. The large leading edge radius of the supercritical airfoil allows high-lift operation without mechanical deflection. Experimental results presented by the paper imply the feasibility of an efficient mono-element cruise and high-lift airfoil, with transition between the two modes accomplished by merely initiating blowing from the fixed trailing edge slot. Comparisons to existing blown and unblown high lift systems are made, and possible applications are discussed.

83. Abramson, J. and E.O. Rogers, "High-Speed Characteristics of Circulation Control Airfoils," Paper AIAA-83-0265 presented at AIAA 21st Aerospace Sciences Meeting, Reno, Nevada (10-13 Jan 1983).

A comprehensive transonic wind tunnel evaluation (0.3 to 0.8 Mach number range) was made of a circulation control (CC) airfoil at Reynolds number of 3 to 7 million. The CC concept employs boundary layer control to augment lift by ejecting air over a rounded (Coanda surface) trailing edge. The purpose of this evaluation was to expand the airfoil data base for aircraft performance prediction and to identifv the compressibility effects on CC aifoils, particularly in regard to lift augmentation capability. Two interchangeable trailing edge contours were evaluated and compared wirh previous configurations. Significant increases in the lift control capability were achieved with one of the designs. The jet slot height was found to have a major influence on the maximum attainable lift and on the plenum pressure ratio at which maximum lift occurs. For the airfoil contours evaluated, there is a correlation between stall (for lift due to blowing) and the apppearance of critical pressure coefficient on the Coanda surface. An instrumentation technique was developei to identify possible hysteresis effect in the stall region.

84. Harris, M.J., "Investigation of a Pneumatic Thrust Deflector Based on Circulation Control Technology," Report DTNSRDC/ASED-83/01, AD A128-950 (Feb 1983).

An investigation was conducted to validate the potential of a pneumatic thrust deflector based on circulation control technology. This thrust deflector consists of a small blown curved surface mounted adjacent to a two-dimensional nozzle. In the configuration evaluated, a 3.5-in. (8.9-cm)-diameter blown surface was used to deflect the exhaust of a 660-lb (2.94-kN) thrust turbojet. Thrust deflection through 65 deg was achieved at reduced thrust levels. This performance was achieved pneumatically without the use of complex moving mechanial parts.

85. Englar, R.J. and G.G. Huson, "Development of Advanced Circulation Control Wing High Lift Airfoils," Paper AIAA-83-1847 presented at AIAA Applied Aerodynamics Conference, Danvers, Massachusetts (13-15 Jul 1983); also published as Report DTNSRDC-83/109, AD A136-585 (Dec 1983).

Recent experimental and flight test programs have developed and confirmed the high lift capability of the Circulation Control Wing (CCW) concept. These CCW airfoils employ tangential blowing of engine bleed air over circular or near-circular trailing edges, and are capable of usable lift coefficients triple those of simple mechanical flaps. Earlier versions of these blown airfoils made use of relatively complex leading and trailing edge devices which would have to be retracted mechanically for cruise flight. In a continuing program to reduce the complexity, size and weight of the CCW system, several series of advanced CCW airfoils have been developed which can provide STOL capability for both military and commercial aircraft using much smaller, less complex high lift systems. The paper will describe these configurations and present the experimental results confirming their aerodynamic characteristics, as well as make comparisons to previous CCW and more conventional high lift sytems.

86. Montana, P.S., "A Time Domain Analysis of a Rigid Two-Bladed Fully Gimballed Helicopter Rotor with Circulation Control," Report DTNSRDC-83/081, AD A136-947 (Dec 1983).

An analytic investigation was made to determine the dynamic properties of a two-bladed rigid fully gimballed helicopter rotor incorporating circulation control airfoils and tip jet propulsion. A time domain analysis was developed which provided the capability of using nonlinear airfoil aerodynamics and arbitrary rotor physical characteristics. The effects of feather principal axis of inertia location, horizontal gust disturbances, and feedback control on rotor stability were assessed. Results of the investigation indicate that the subject helicopter rotors are unstable in forward flight without feedback control. With feedback, the rotors are stable and controllable.

87. Wilkerson, J.B., "A Model of Rotor Blade First Natural Flapping Response for Up to Three/Rev Excitations," Report DTNSRDC/ASED-83/09, AD A141-725 (Dec 1983).

Thus far, all performance calculations for the X-Wing vertical takeoff concept have used a rigid nonflapping blade analysis. At this stage in the concept development, the flapping degree of freedom should be included for increased accuracy. Thus, a relatively simple set of equations is developed to relate rotor blade aerodynamic moments and blade flapping repsonse which provides rapid evaluation of the blade dynamics and the resulting changes in aerodynamic loading. The relationships between the aerodynamic hinge moments and the blade response are derived for the first three harmonics of flapping. Changes in flap damping due to flapping response are accounted for in the equations, which are solved using standard matrix algebra. The equations are validated by comparison with a more sophisticated analytical technique. A case is examined for the critical conversion advance ratio, and the first-order dynamic response is shown for a range of blade natural frequencies. It is shown that a blade natural frequency higher than 2-per-rev is desired.

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Recent investigations proved the compatibility of the Circulation Control and the Upper Surface Blowing concepts. This static investigation is a follow-up to determine what combinations of geometric and pneumatic variables produce an effective deflection of a thick wall jet by a thin wall jet exhausting over a rounded corner. Static pressure distributions over the corner indicate that maximum deflections of the thick wall jet occur when a high average suction is distributed over the surface of the corner. Using a large corner radius, locating the source of the thick wall jet somewhat upstream from the corner and the thin wall jet source, and using a high aspect ratio thick wall jet are geometric means of producing this type of pressure distribution.

APPENDIX
SELECTED OUTSIDE REFERENCES PERTINENT TO CIRCULATION CONTROL

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